EXPERIMENTAL STUDY OF TURBULENT SPIN-DOWN FLOWS OF LIQUID SODIUM

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Summary The free decay of liquid sodium flow (at Reynolds number up to 3 000 000 and magnetic Reynolds number up to about 30) generated by the sudden stop of a rapidly rotating toroidal channel is studied experimentally. The toroidal and poloidal components of velocity are measured using a potential probe, the magnetic field is measured by coils and Hall probes. We describe the onset of motion, the evolution of strongly anisotropic fluctuations, and the homogenization and decay of turbulence in the final period. We analyze the statistical characteristics of velocity fields and estimate the turbulent viscosity in relation to the behavior of effective magnetic diffusivity estimated from measurements of the phase shift between the induced and applied magnetic fields. We study also a *screw* spin-down flow of liquid sodium, generated in the same channel by diverters installed in the channel.

INTRODUCTION

The screw flow is one of basic flows studied by the dynamo theory and became the base of the first experimental set-up for laboratory study of dynamo [1]. From the point of view of laboratory facility it is very attractive to get a required for dynamo action flow in a confined and compact device. The most compact screw flow can be suggested in a toroidal geometry, in which the flow is generated by abrupt braking of rotating torus [2]. The feasibility of a screw flow in the torus is not obvious, since the angular momentum conservation law prevents the turning of the screw along the curved channel. First experiment with spin-down flow of water was done in a transparent channel with one diverter and demonstrated what the large-scale flow perfectly follows the screw trajectories [2]. The curvature of the channel is defined by the aspect ratio $\Gamma = R/r$ (here R is the radius of the torus and r is the radius of the cross-section). In the water experiment $\Gamma = 3.8$, i.e. the torus was relatively thin. In this paper we present result of experimental study of the spin-down flow of liquid sodium in a torus with $\Gamma = 2.25$. We start by experiments with a free channel, in which we analyze the statistical characteristics of velocity fields and estimate the turbulent viscosity in relation to the behavior of effective magnetic diffusivity. After that we study the *screw* spin-down flow, generated by diverters, installed in the channel.

EXPERIMENTAL SETUP

We study spin-down flows of liquid sodium in a toroidal channel made of titanium alloy. The torus radius $R = 0.18$ m, and the radius of the channel cross-section $r_0 = 0.08$ m. The channel is fastened to the horizontal axis, which is also used for mounting a driving pulley, a system of sliding contacts and a disk braking system. The rotation frequency of the channel is up to 50 rps, and the flow in the channel is generated by abrupt braking. The braking time does not exceed 0.3 sec. Two diverters can be fixed in diametrically opposite cross-sections of the channel.

For velocity measurements, we use a 2-axis local potential probe. The probe is mounted on the wall so that its one axis is parallel to the local toroidal direction (along the channel) and its other axis is in the poloidal direction. Thus, we measure the local values of the toroidal $v_{\rm tor}$ and poloidal $v_{\rm pol}$ components of velocity. A bobbin, wound around the channel is supplied by stabilized direct current and produces the toroidal field. We measure three components of the induced magnetic field $\vec{b}$ by a 3D Hall probe, located in the channel cross-section opposite to the position of the velocity probe. The probe can move in the tube of diameter 10 mm, which cross the channel and is parallel to the axis of rotation. The magnetic diffusivity of the metal inside the channel had been estimated by measuring the phase shift between the currents in two coils wound around the channel [3]. A generator created in the toroidal coil a stabilized sinusoidal current with frequency $30 < f < 1000$ Hz, which produced an alternating toroidal magnetic field inside the channel. Besides the toroidal coil, two diametrically located magnetic-test coils were wound around the channel.

SPIN-DOWN FLOW IN A FREE CHANNEL

At the first stage of braking the toroidal velocity of the fluid with respect to the halting vessel increases. The maximum of the toroidal fluid velocity is reached as the vessel stops. The generation of poloidal velocity is provided by the curved channel and becomes more effective with increasing "thickness" of the torus. For the maximal rotation rate, $\Omega = 50$ rps, at the end of braking the ratio of poloidal to toroidal mean velocities reaches $U^{\rm pol}/U^{\rm tor} = 0.18$. The maximal toroidal velocity $U^{\rm tor} = 0.69 V_0 = 39$ m/s, where V_0 is the velocity of the sodium on the channel axis before the brake. The decay starts at the end of braking and can be separated in two stages, transient and final. The final stage starts at $t \approx 1.5 - 2$ s and displays the power law decay for both velocity components, $U^{\rm tor} \sim U^{\rm pol} \sim t^{-1}$. Note, that the mean poloidal velocity is essentially weaker as the toroidal flow, but the poloidal pulsations are stronger at the transient stage, and both the poloidal and toroidal pulsations tend to the same power law of evolution as the mean flow, i.e., $u_{\rm rms} \sim t^{-1}$ (Fig. 1). The turbulence level defined as $u^{\rm pol}_{\rm rms}/U^{\rm tor}$ reaches its maximum near the end of the braking. During the transient stage, the turbulence level goes down and remains stable at the final stage of evolution, which means that in the decay the rms

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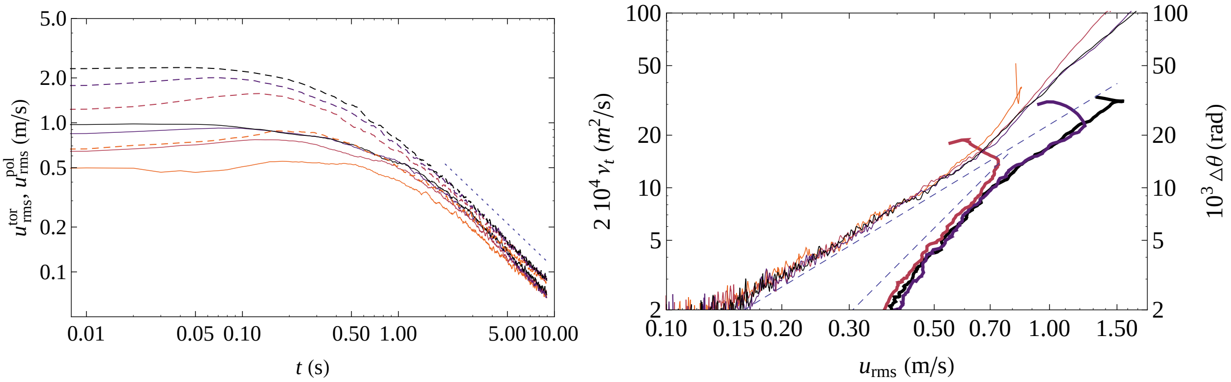

Figure 1. Left: decay of mean-root-square pulsations of toroidal (solid lines) and poloidal (dashed lines) components in log-log coordinates. Right: turbulent viscosity (thin upper lines) and turbulent magnetic diffusivity (thick lower lines) versus root-mean-square velocity fluctuations. Two dashed lines correspond to power laws $u_{\rm rms}^{1.3}$ (above) and $u_{\rm rms}^{2}$ (below).

pulsations are proportional to the mean toroidal velocity. This is consistent with the analogous decay law for the mean velocity and pulsations. The maximum of the turbulence level coincides in time with the maximum of anisotropy. At this moment the poloidal pulsations exceed the toroidal pulsations by a factor of 2.4. At the late stage of evolution, the small constant anisotropy still remains valid ($u^{\rm pol}_{\rm rms}/u^{\rm tor}_{\rm rms} \approx 1.2$), showing weak dominance of poloidal pulsations in the domain of velocity measurements.

TURBULENT VISCOSITY AND TURBULENT DIFFUSIVITY

The turbulent viscosity has been estimated from the mean flow decay rate and using the Kolmogorov-Prandtl formula $\nu_t = CE_t^2/\epsilon$, where C is a dimensionless prefactor of the order of unity, $E_t = (u^{pol}_{rms})^2$ is an estimation of the energy of turbulent pulsations and $\epsilon = \partial(U^{tor})^2/\partial t$ is an estimation of the kinetic energy dissipation rate. Both definitions provide similar behavior for the turbulent velocity, displaying a power-law decay at the late stage of evolution. For $t > 1$ s, we get $\nu_t \sim t^{-1.3}$. In our experiments, the indicator of an increase in magnetic diffusivity was the phase shift between the induced and applied alternating magnetic fields. Note that the measured phase shift corresponds to the averaged magnetic diffusivity in the whole mass of liquid sodium, while the velocity measurements are done in one fixed point of the flow. In Fig. 1 we show the turbulent viscosity and the turbulent magnetic diffusivity versus root-mean-square velocity fluctuations. For the decaying stage of evolution, the results obtained at different initial rotation rates of the channel are very close and display a pronounced power-law dependence on the intensity of turbulent pulsations, namely, $\nu_t \sim u_{\rm rms}^{1.3}$. The effective magnetic diffusivity shows different behavior at low and high levels of turbulent pulsations. At low $u_{\rm rms}$, diffusivity increases much faster than viscosity and at high $u_{\rm rms}$, the slope for diffusivity tends to the slope for viscosity, i.e., $\eta_t \sim u_{\rm rms}^{1.3}$. The transition from one power-law to another occurs when the magnetic Reynolds number, defined via the rms velocity pulsations, is of order of unity.

SCREW SPIN-DOWN FLOW

Experiments made with water spin-down flow in a relatively thin torus ($\Gamma = 3.85$) showed that the *screw* flow, generated by diverters installed in the channel, decays faster as the flow in the free channel, but evolves in similar way [2]. The toroidal velocity steadily increased up to the end of braking but the maximum of the toroidal velocity decreased in comparison with the free channel by a factor of about 2-3, depending of the number of diverters. The free decay at late stage of evolution followed a power law, also similar to the behavior in the free channel. The spin-down screw flow in experiments under discussion displayed a completely different behavior. Both velocity components measured at the half of the arc between two diverters showed strong oscillations during the braking.The grows of toroidal component during the braking alternates with strong decreases. The poloidal component displays strong oscillations around the zero. The dissipation of energy is extremely strong - only about 10% of kinetic energy survived at the end of the braking.

References

[1] A. Gailitis et al., *Phys. Rev. Lett.*, **84**: 4365, (2000).
[2] S. A. Denisov, et al. *Physics - Doklady*, **44**: 231Ű233, (1999).
[3] P. Frick, et al., *Phys. Rev. Lett.*, **105**: 184502, (2010).